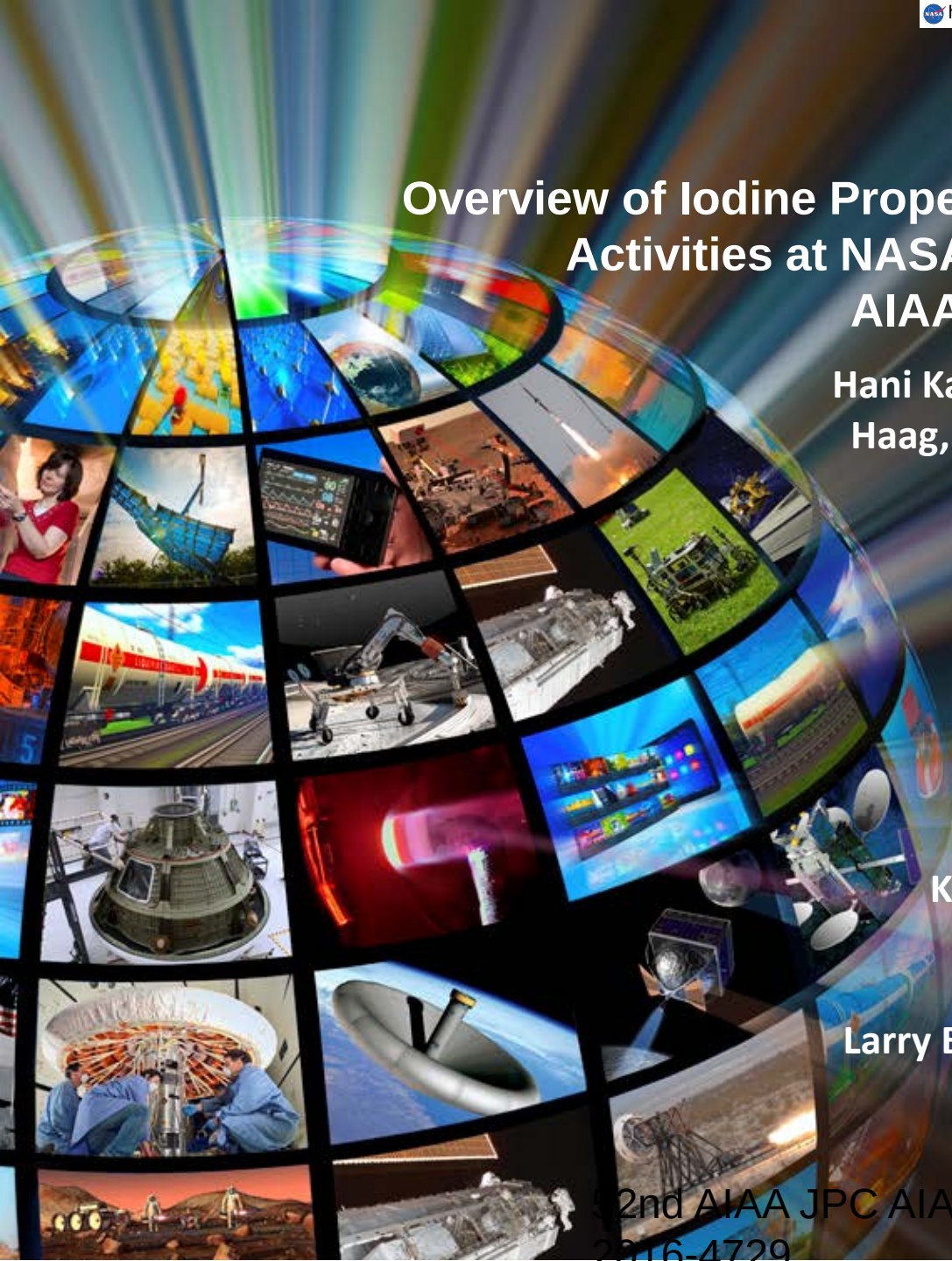
National Aeronautics and Space Administration



Overview of Iodine Propellant Hall Thruster Development Activities at NASA Glenn Research Center AIAA-2016-4729

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Outline

- **Motivation**
- **Objectives**
- **iSAT project overview**
- **Advanced In Space Propulsion Project**
- **NASA GRC activities**
  - Thermal modeling
  - Test facilities at NASA GRC
  - Thruster testing
    - BHT-200-I
    - BHT-600-I
- **Summary**

Motivation: Iodine Big Picture

- **High Expectation of Mission Infusion**
  - Characteristics of some iodine propelled EP thrusters are attractive to multiple sectors of electric propulsion market

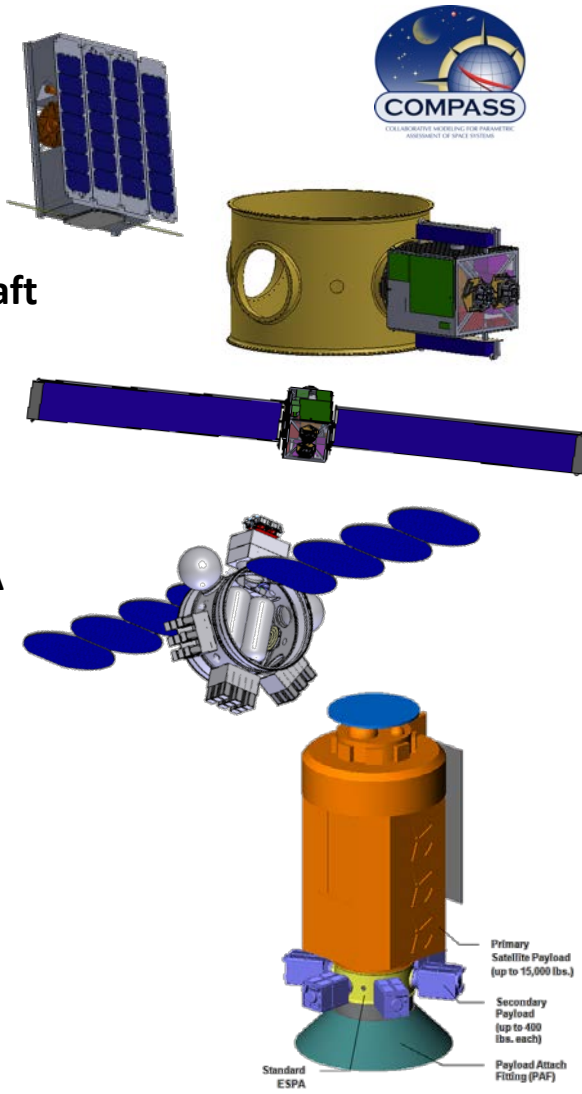
- **The market is trending to both higher and lower power (<1kW and >10kW)**
  - High power
    - Storage density has system level impacts
    - Lower facility pumping speed requirements for space environment simulation
  - Low Power
    - I_{SP}-Density is enhancing for Small Sats (10kg – 180kg)
    - Benign solid stored indefinitely unpressurized – secondary payload

- **Iodine properties are ideal for secondary payloads**
  - Benign propellant storage, quiescent until heated
  - Can be launched and stored unpressurized
  - High density ~4.9 g/cm^3 and high Density – I_{SP} ~ 7,500 g-s/cm^3
    - Xe ~2,500 g-s/cm^3, Solid Motor ~500 g-s/cm^3, Cold Gas ~150 g-s/cm^3
  - Enhanced orbit maneuverability (plane change and altitude change)

Mid-Term Iodine Objectives

Multiple COMPASS Studies Completed on Iodine Mission Applications:

- **200 W Iodine is enabling for NanoSats (1-10kg) and MicroSats (10-100kg)**
- **200W – 600W Iodine Enhances high ΔV for ESPA class (180kg) spacecraft**
  - Can provide ~10km/s ΔV (More than 2x the Xenon ΔV capability (Volume limited))
  - Enables GTO to Asteroids, Mars and Venus (Iodine and Xenon can both go to the moon)
- **600W Iodine Enhances "Discovery Class" Science Instruments for ESPA Grande class (300kg) spacecraft**
  - Volume limitations require high density propellant
    - 3x – 5x reduction in total mission cost
    - New class of SMD missions (3X the science)
- **600W – 1.5KW Class Iodine Enhances Orbit Maneuvering Systems**
  - Iodine based ESPA OMS can enhance high ΔV using the volume within the ESPA ring
  - Can increase payloads over Xenon from GTO to GEO
  - Can enable independent payload delivery to various Mars orbits



iSAT Mission Concept

The iSAT Project is maturating iodine Hall technology to enable high ΔV primary propulsion for NanoSats (1-10kg), MicroSats (10-100kg) and MiniSats (100-500kg) with the culmination of a technology flight demonstration

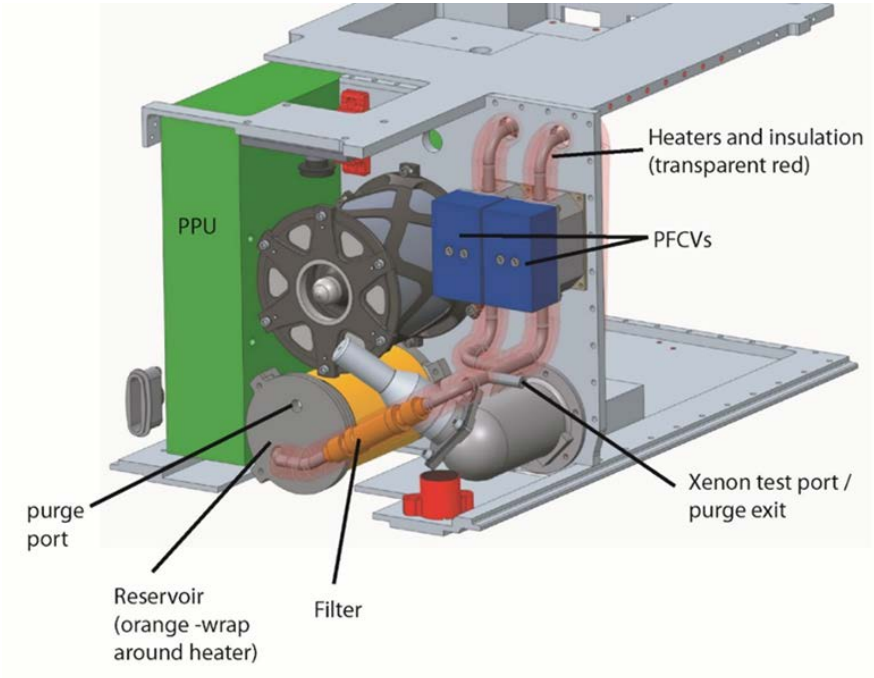
- NASA MSFC is leading the propellant feed system development, spacecraft system development and operations
- NASA Glenn is leading the technology development and is the flight propulsion system lead
- Busek Company Inc is the flight propulsion system provider

iSAT Project launches a small spacecraft technology demonstration into low-Earth orbit to:

- Reduce risk for future iodine missions
- Evaluate iodine spacecraft interactions (limited)
- Demonstrate overall system operation in space
- Demonstrate new power system technology for SmallSats
- Demonstrate new class of thermal control for SmallSats
- Gain knowledge on iodine environment impact to payloads (limited)
- Increase expectation of follow-on missions

Iodine Satellite (iSat)

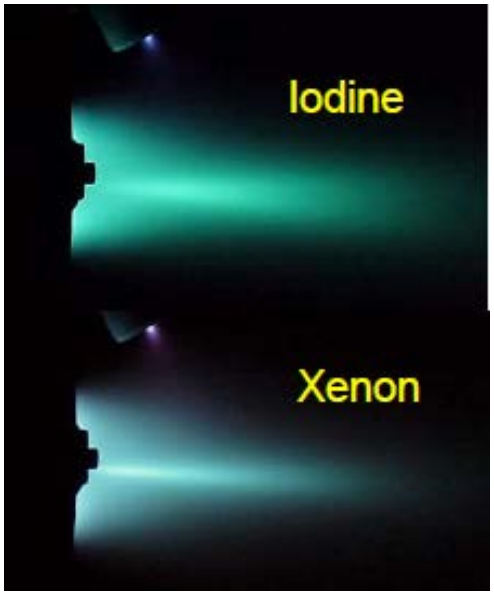
- **12U "CubeSat" will demonstrate iodine propellant on orbit for t first time**
  - To be launched as a secondary payload
  - ~20 hours on-orbit demonstration of iodine fueled Busek BHT-200 Hall thrus
  - 0.25 kg of propellant



Advanced In-Space Propulsion Project

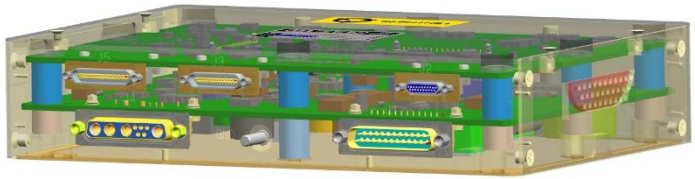
Space Technology Mission Directorate – Game Changing Program

- **Leveraging previous Small Business Innovative Research (SBIR) work with Busek for development and testing of**:
  - 600W Hall thruster based on BHT-200
  - Brassboard modular power processing unit
  - Iodine compatible cathodes and feed system components
- **NASA GRC has vacuum test facilities that can be used to evaluate iodine propulsion devices up to 4-kW**
- **Task will address critical Technology Gaps and Risks**
  - Scale up to higher power
  - Engineering/material changes and validation, valve wetting surfaces and seals
  - Propellant flow rate and metering is critical to achieve required performance
  - Wear testing >1000hrs for both thrusters and cathodes
  - Spacecraft / plume interactions testing and analyses
- **Leveraging development with NASA iSAT 12U demonstration mission**
  - 200W iodine Hall propulsion system flight demonstration through NASA Small Spacecraft Technology Program

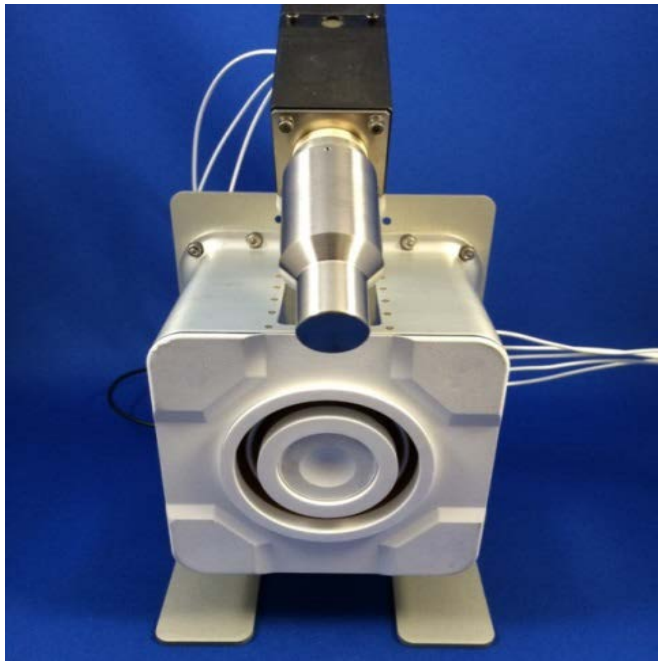


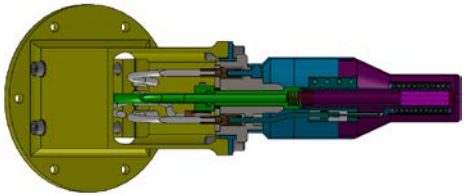
Advanced In-Space Propulsion Project
600W Busek Iodine Hall system

Power Processing Unit

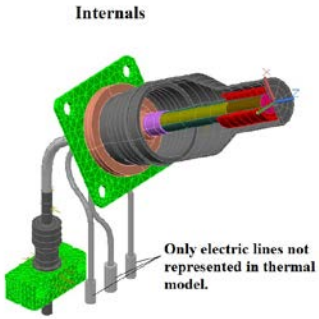


BHT-600-I Thruster



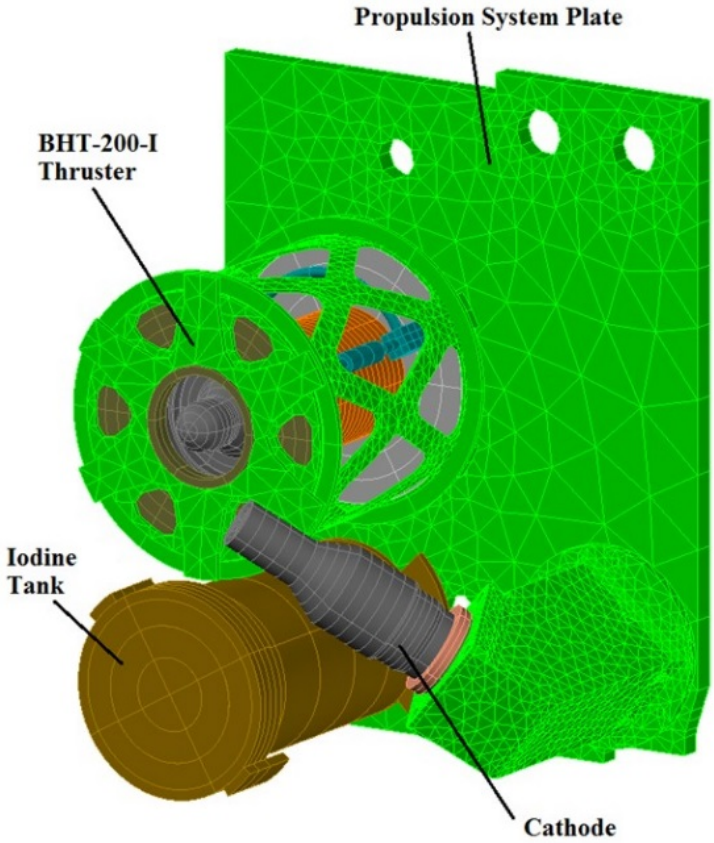


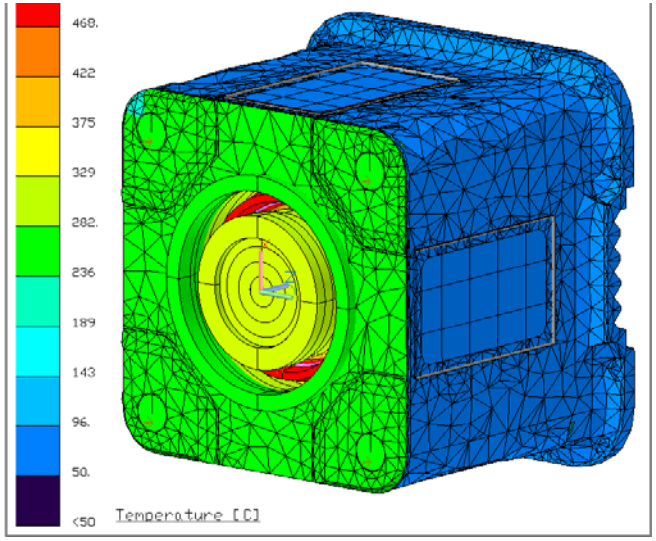
Cathode



Thermal Modeling

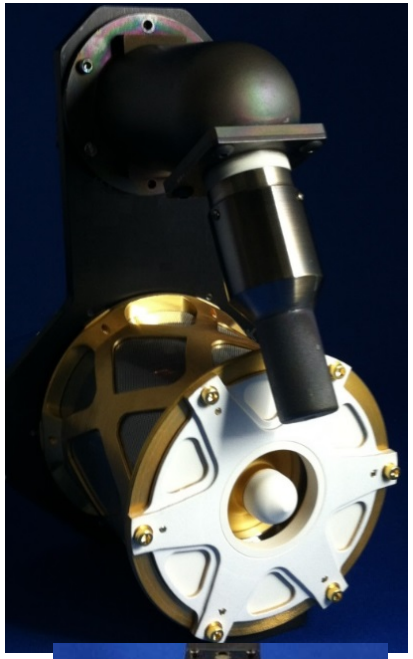
- NASA GRC is performing detailed thermal modeling of the iSAT propulsion system and the BHT-600-I thruster
- iSAT components being modeled include the BHT-200-I, iodine feed system, cathode, and PPU



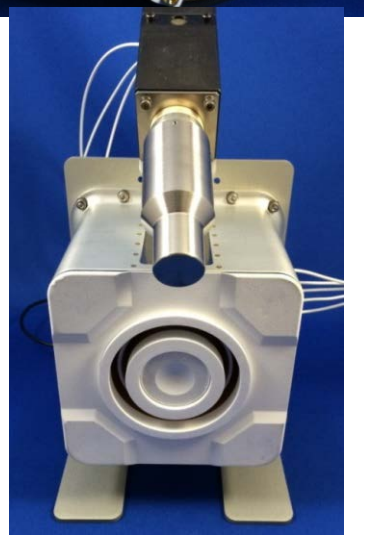


Busek BHT-200-I & BHT-600-I Thrusters

- **BHT-200-I**
  - Derivative of the flight BHT-200 that was the first US designed and manufactured Hall thruster flown in space (FalconSat-5)
  - The BHT-200-I is distinguished from the BHT-200 by the materials of construction, geometry of the anode, and iodine resistant coatings

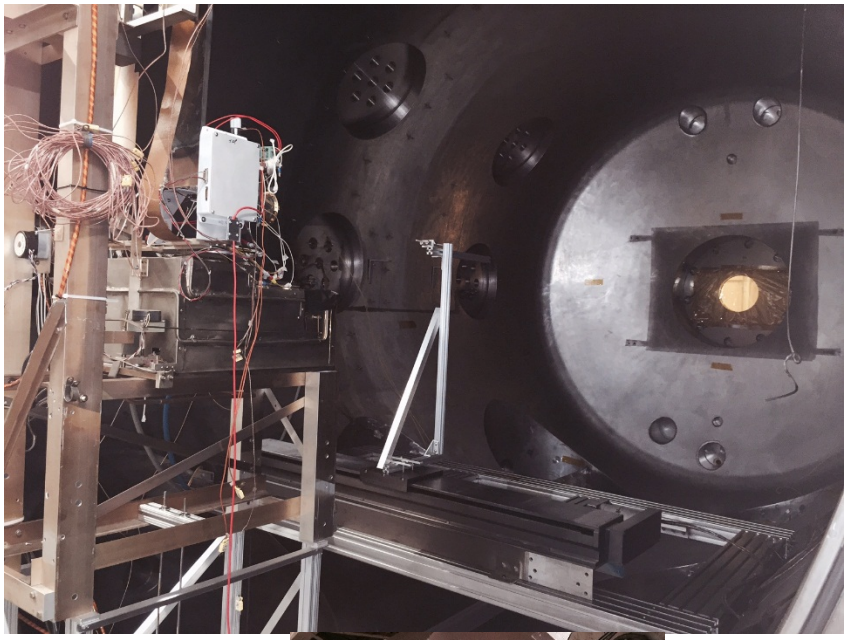


- **BHT-600-I**
  - Derivative of the TRL-6 BHT-600
  - The 600 W thruster is sized for satellite station keeping and orbit maneuvering



Test Facility: VF-7

- **Test of the BHT-200-I will be performed in VF-7**
- **VF-7 is 10 ft. in diameter and is 15 ft. long**
- **VF-7 is evacuated with 5 ODPs**
  - Base pressure is ~$5X10^{-7}$ Torr and is expected to be ~$2X10^{-6}$ Torr during testing
- **LN_2 cooled dense chevrons will be used to collect the exhausted iodine**
- **VF-7 uses vent lines and heat lamps to facilitate exhausting of the iodine propellant at the conclusion of testing**

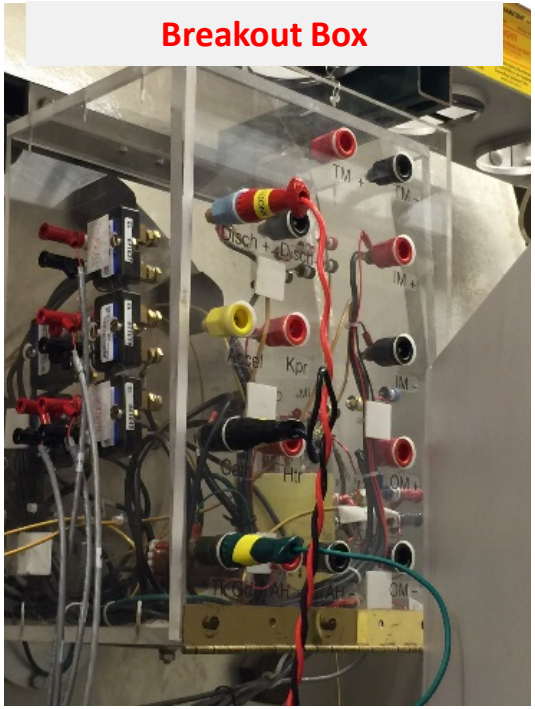


Data Collection & Control Upgrades

- VF7 has been upgraded with a new power supply, data acquisition, and control rack.
- Permits unattended testing, remote monitoring, and evaluation of propulsion system control algorithms.
- Dedicated power supplies for discharge, cathode, magnets, keeper, auxiliary boards, valves, and powered sensors.
  - Programmable control via high voltage isolated RS485
- National Instruments DAQ
- Battery power backup on data acquisition equipment

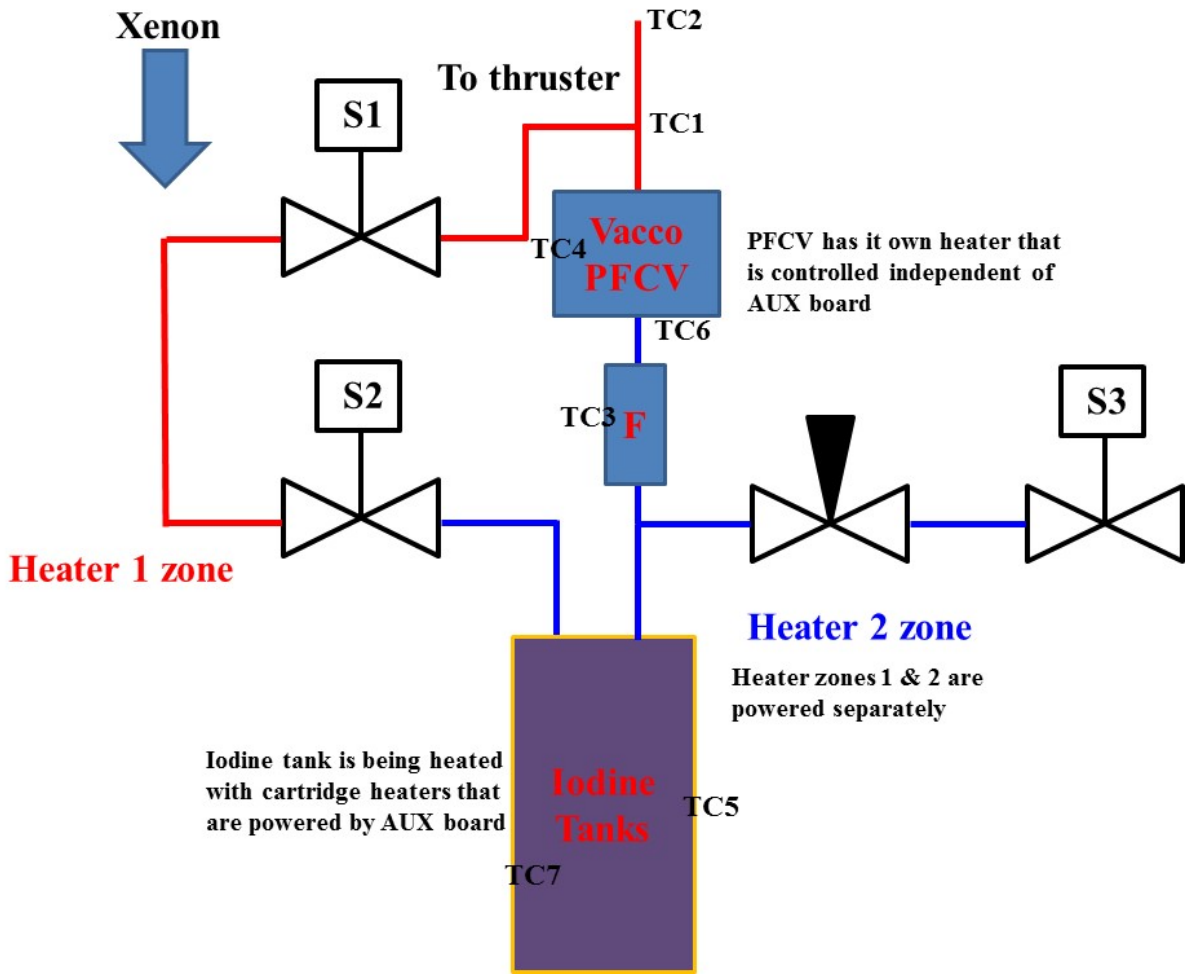
Breakout Box

- **A breakout box was fabricated for use with VF7 Hall thruster testing:**
  - Voltage dividers to measure discharge and keeper voltage
  - Current shunts to measure heater, cathode, keeper, and electromagnet currents
  - Provision for changing the “filter” between the PPU and the thruster
  - Sense wires

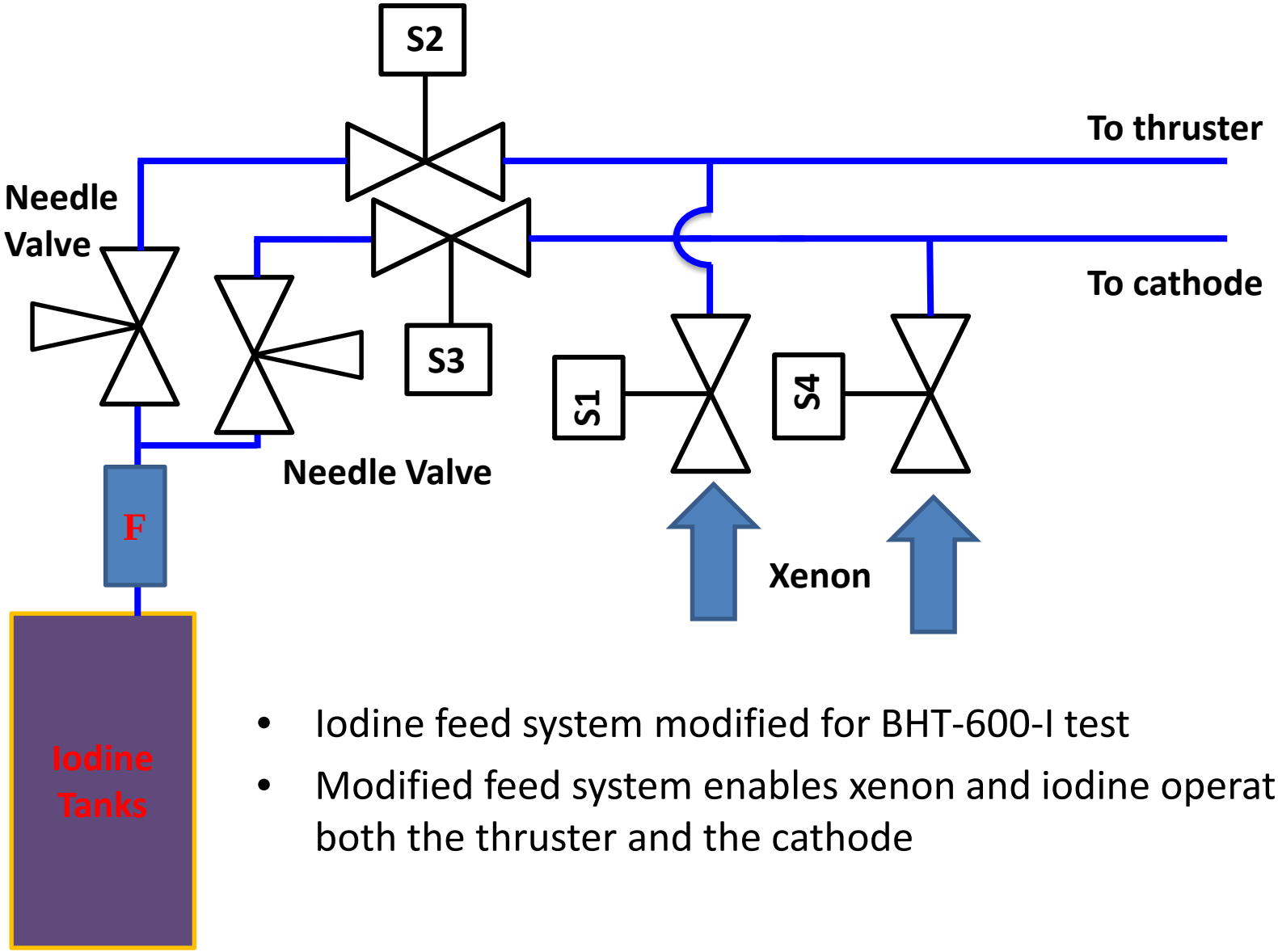


Iodine Feed System: BHT-200-I

- A laboratory iodine propellant feed was designed, fabricated, and assembled at NASA GRC
- VACCO iodine compatible PFCV was integrated with iodine feed system
- Iodine feed system allows for option to operate the thruster with xenon or iodine propellant



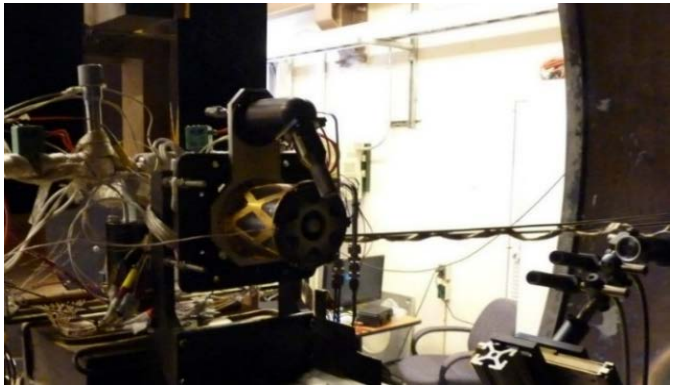
Iodine Feed System: BHT-600-I



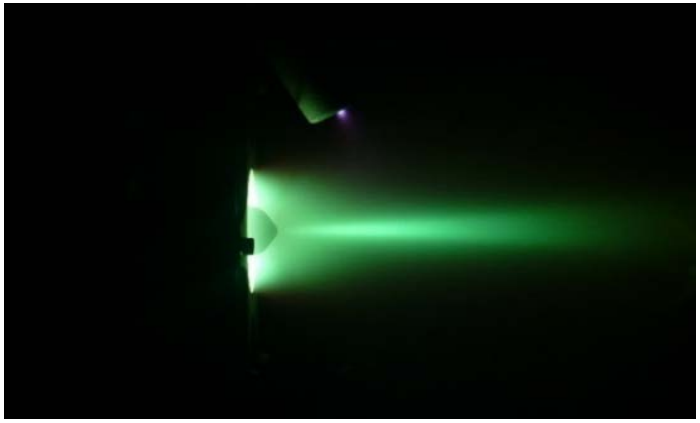
- Iodine feed system modified for BHT-600-I test
- Modified feed system enables xenon and iodine operation for both the thruster and the cathode

BHT-200-I Tests

- **The objectives of the duration test of BHT-200-I were:**
  - Validate the design modifications of the EM thruster prior to building the qualification and flight model thrusters;
  - Measure the thrust produced by thruster when fueled with xenon and iodine;
  - Measure temperatures of selected thruster components to confirm design thermal viability and to provide critical data for thermal model validation; and
  - Demonstrate robust and reliable PFCV operation.
- **80 hours of cumulative hot-fire thruster operation was attained on the thruster over 6 days**

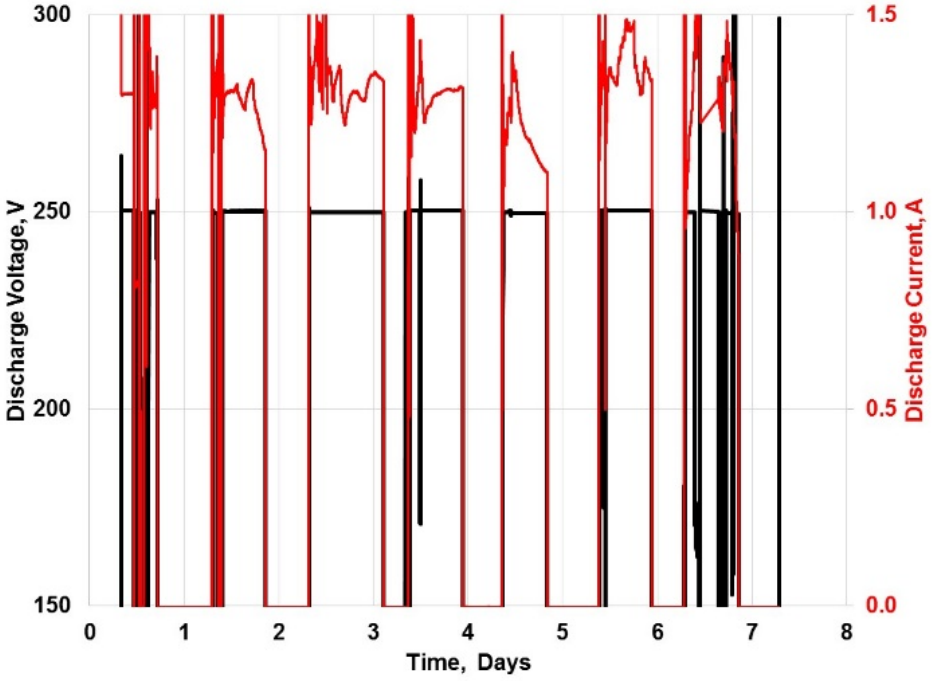


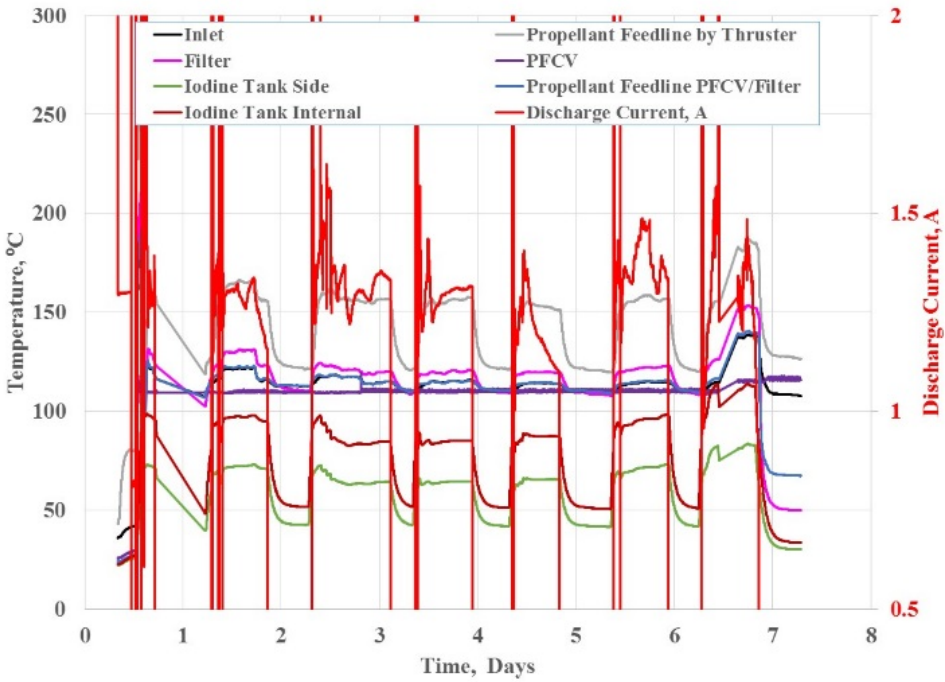
BHT-200 thruster and iodine feed system installed on the inverted pendulum thruster stand in VF–7



BHT-200-I Tests

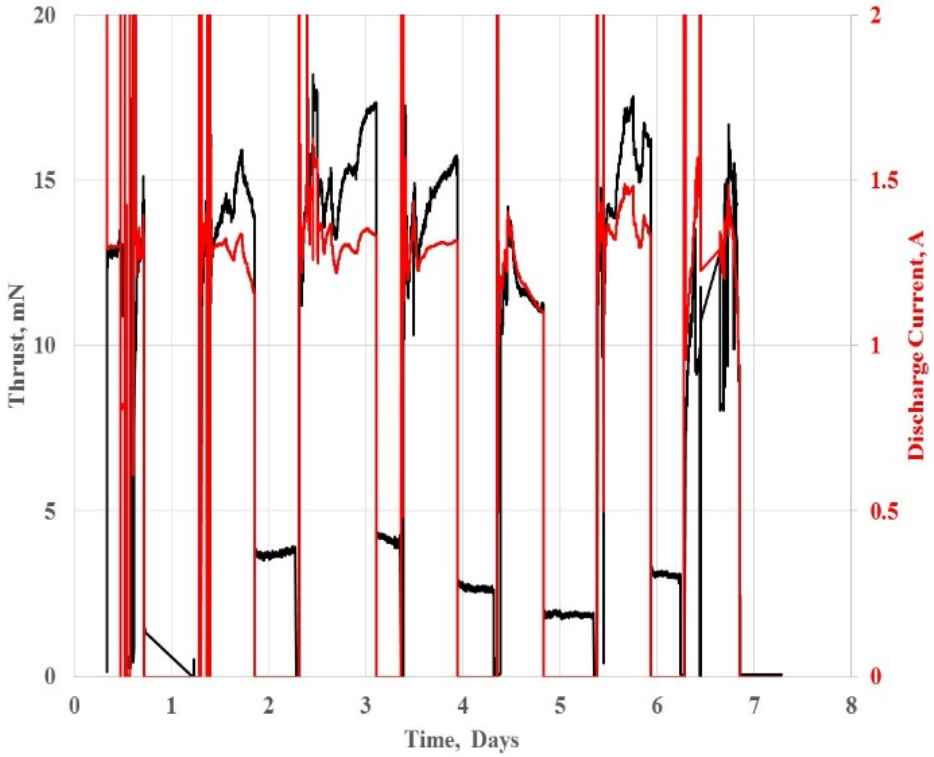
- 80 hours of hot-fire operation was attained on the BHT-200-I
- Throughout the test the thruster telemetry and iodine feed system temperatures were monitored and manually controlled to maintain iodine flow to the thruster

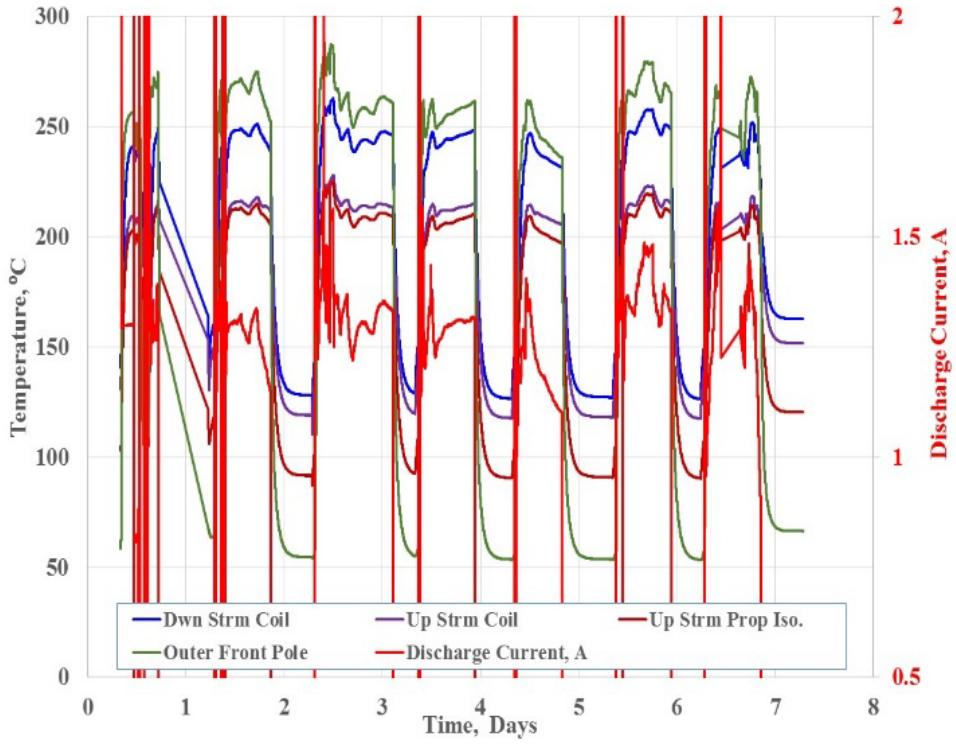




BHT-200-I Tests

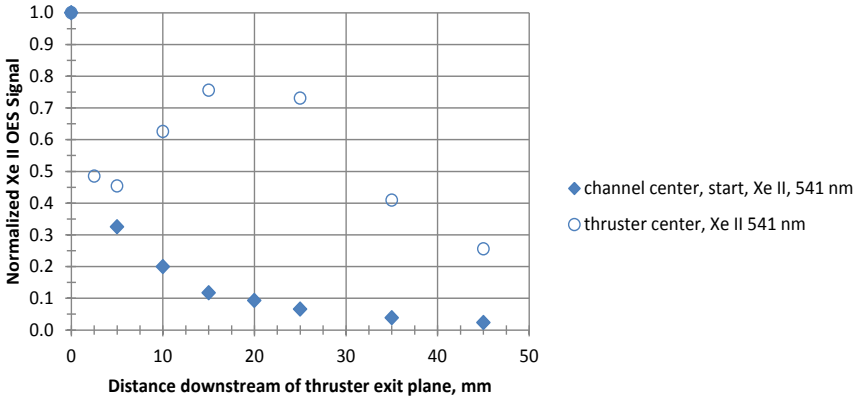
- Thruster performance and component temperatures were monitored during the test
- The measured thruster component temperatures were used to confirm the thruster's thermal design integrity and to compare with the thermal model results

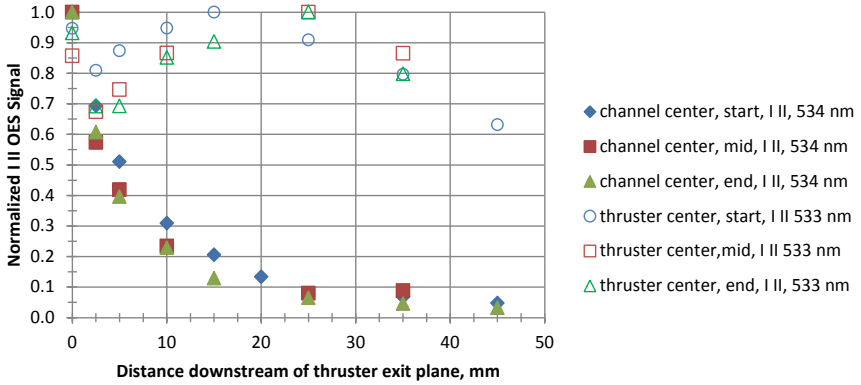




BHT-200-I Tests

- OES plume results indicated that the xenon and iodine plumes have similar structure



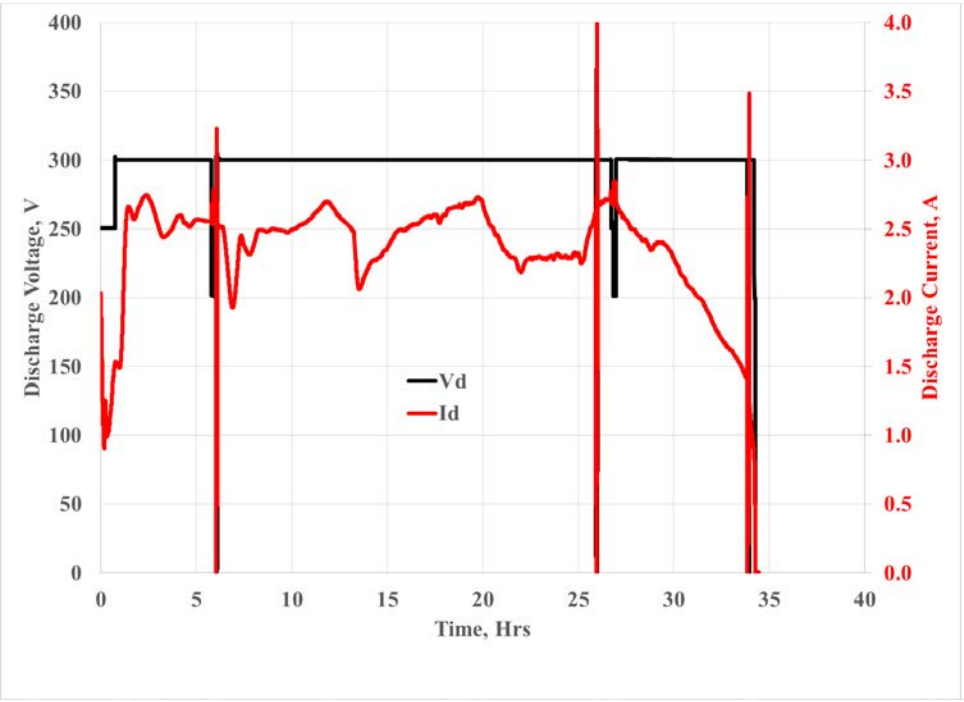


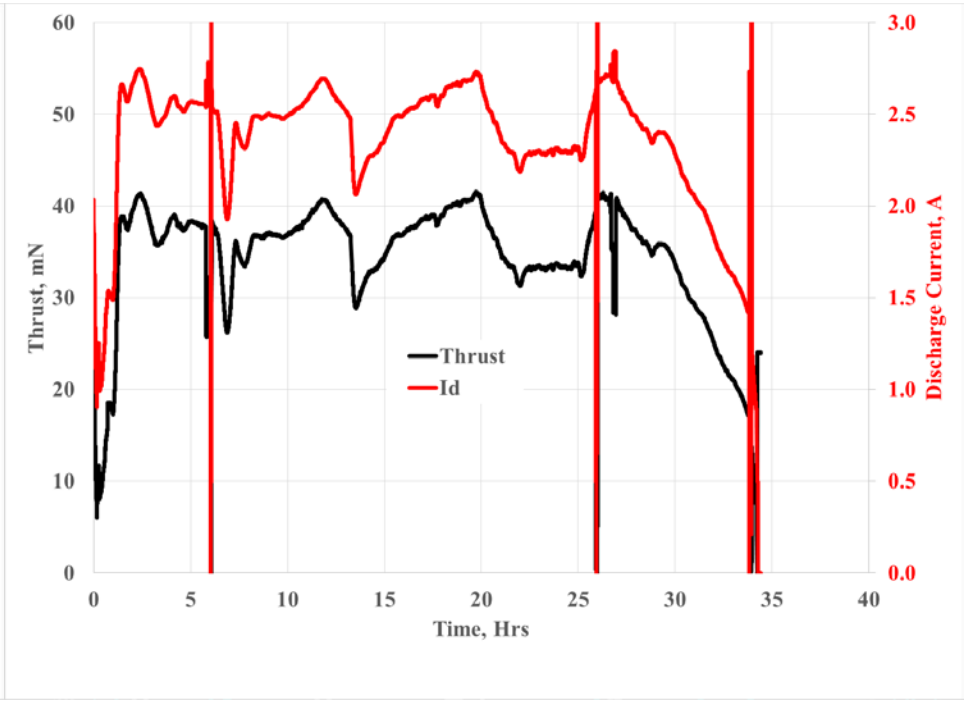
- Pre and post duration test performance comparison indicate that the thruster performance did not change
- Detailed post test thruster inspection indicated that no degradation to the thruster occurred due to prolonged iodine exposure

	0 hour		80 hour	
	Xenon	Iodine	Xenon	Iodine
Discharge Voltage, V	250	250	250	250
Discharge Current, A	0.81	0.83	0.80	0.84
Thrust, mN	12.9	14.2	13.2	13.9

BHT-600-I Tests

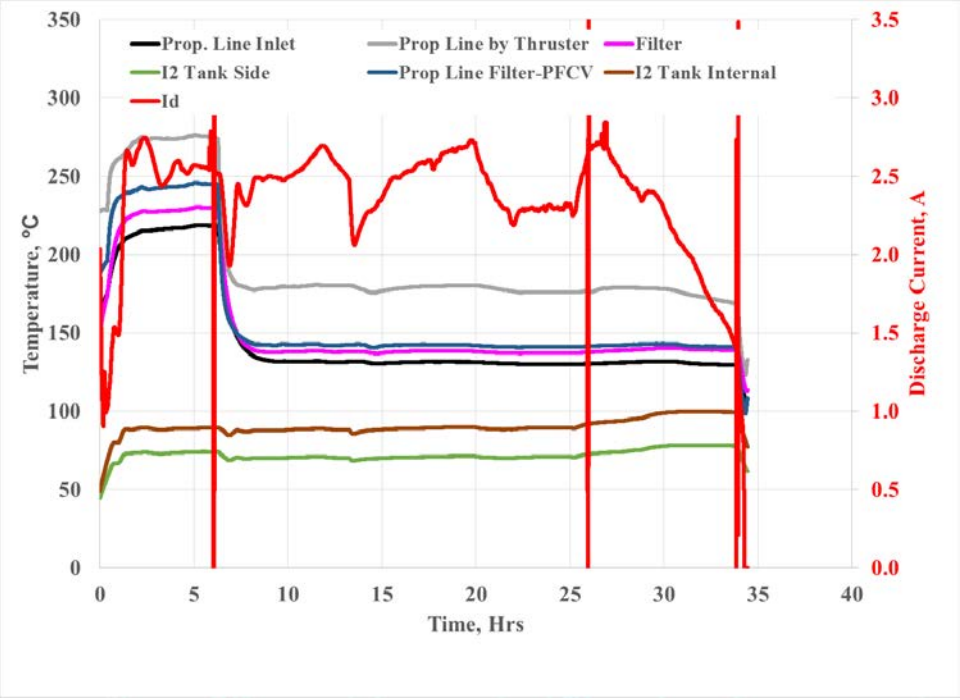
- Two duration tests of the BHT-600-I thruster were performed
- The BHT-600-I tests utilized the laboratory iodine feed system w/o the PFCV
- Thermal throttling was used to regulate the iodine flow rate
- The first duration test (34 hrs) was run attended

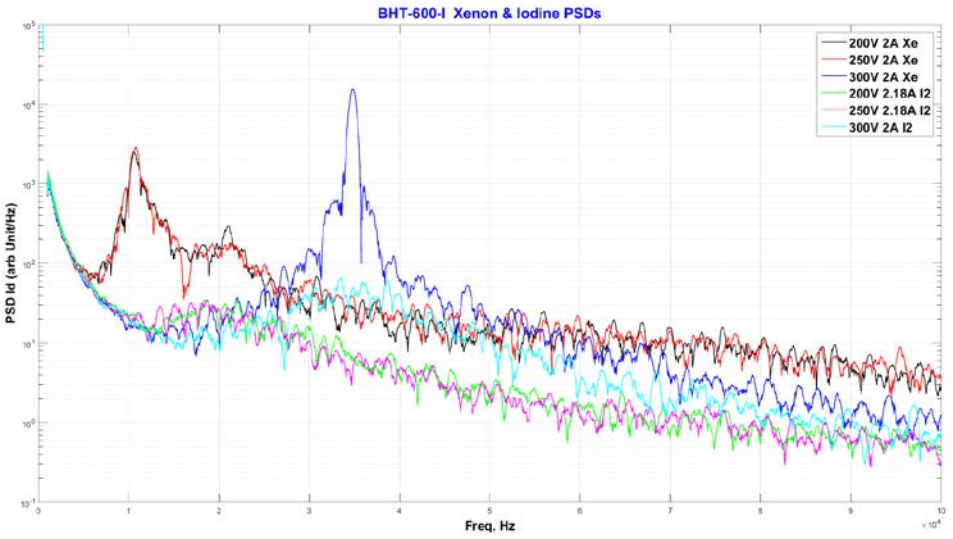




BHT-600-I Tests

- Manual control of the various iodine feed system component temperatures was used to regulate the iodine flow to the thruster
- The xenon and iodine PSDs show different profiles, different dominant frequency





BHT-600-I Tests

- Pre and post duration test performance comparison indicate that the thruster performance did not change
- Detailed post test thruster inspection indicated that no degradation to the thruster occurred due to prolonged iodine exposure

	0-hr		34-hr	
	Xenon	Iodine	Xenon	Iodine
Discharge Voltage, V	300	300	300	300
Discharge Current, A	2	2	1.98	2
Thrust, mN	38.4	39.2	39.4	38

Summary

- NASA continues to develop iodine Hall thrusters due to mission benefits for small spacecraft
- The team of NASA GRC, NASA MSFC, and Busek Co. Inc. are working on both a flight mission and technology development activity
- The Busek QM BHT-200-I thruster and QM feed system will be qualified for flight on the iSAT mission
- The BHT-600-I development activity will culminate in the delivery of an engineering model BHT-600-I Hall thruster PPU
  - An engineering model Hall thruster was developed and delivered under a Phase II SBIR
- To date, extended duration tests have been conducted at NASA GRC on the EM BHT-200-I and BHT-600-I Hall thrusters
  - In each test the thruster performance was consistent with previous observed results and in-line with operation on xenon
  - Post inspection of the thrusters did not show any significant physical changes after operation with iodine

Future Activities

- **Future near-term activities include:**
  - Component level propellant isolator tests
  - Component level tests of iodine-compatible cathode assemblies. Busek and NASA GRC-designed and manufactured cathode assemblies will be evaluated with iodine propellant and a reduced set of assemblies will be duration tested
  - Integrated testing of the EM BHT-200-I with a Busek iodine-compatible cathode assembly. This test will incorporate two modified Gen 1 PFCVs, and the feed system configuration will be very similar to the iSAT spacecraft iodine feed system. This test will include cyclic tests on the BHT-200-I thruster to simulate operation on the iSAT spacecraft
  - Upgrades to VF-7 to reduce operational costs and enhance iodine removal after testing
  - Integrated testing of the qualification model BHT-200-I thruster with the iSAT qualification iodine feed system
  - Integrated testing of the BHT-600-I thruster with the PPU being developed by Busek.
  - Extended duration testing of the BHT-600-I thruster to show its viability to meet projected NASA missions

Acknowledgments

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